Received 2007 April 10; accepted 2007 May 7
Preprint typeset using LaTeX style emulateapj v. 6/22/04

X-RAY TIMING OF PSR J1852+0040 IN KESTEVEN 79: EVIDENCE OF NEUTRON STARS WEAKLY MAGNETIZED AT BIRTH

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Received 2007 April 10; accepted 2007 May 7

ABSTRACT

The 105-ms X-ray pulsar J1852+0040 is the central compact object (CCO) in supernova remnant Kes 79. We report a sensitive upper limit on its radio flux density of 12 μJy at 2 GHz using the NRAO Green Bank Telescope. Timing using the *Newton X-Ray Multi-Mirror Mission* (*XMM-Newton*) and the *Chandra X-ray Observatory* over a 2.4 yr span reveals no significant change in its spin period. The 2σ upper limit on the period derivative leads, in the dipole spin-down formalism, to an energy loss rate $\dot{E} < 7 \times 10^{33}$ ergs s^{-1}, surface magnetic field strength $B_p < 1.5 \times 10^{11}$ G, and characteristic age $\tau_c \equiv P/2\dot{P} > 8$ Myr. This value of τ_c exceeds the age of the SNR by 3 orders of magnitude, implying that the pulsar was born spinning at its current period. However, the X-ray luminosity of PSR J1852+0040, $L_{\rm bol} \approx 3 \times 10^{33}\,(d/7.1~{\rm kpc})^2$ ergs s^{-1}, is a large fraction of $\dot{E}$, which challenges the rotation-powered assumption. Instead, its high blackbody temperature $kT_{\rm BB} = 0.46 \pm 0.04$ keV, small blackbody radius $R_{\rm BB} \approx 0.8$ km, and large pulsed fraction $f_p \approx 80\%$, may be evidence of accretion onto a polar cap, possibly from a fallback disk made of supernova debris. If $B_p < 10^{10}$ G, an accretion disk can penetrate the light cylinder and interact with the magnetosphere while resulting torques on the neutron star remain within the observed limits. A weak B-field is also inferred in another CCO, the 424-ms pulsar 1E 1207.4−5209, from its steady spin and soft X-ray absorption lines. We propose this origin of radio-quiet CCOs: the magnetic field, derived from a turbulent dynamo, is weaker if the NS is formed spinning slowly, which enables it to accrete SN debris. Accretion excludes neutron stars born with both $B_p < 10^{11}$ G and $P > 0.1$ s from radio pulsar surveys, where $B_p < 10^{11}$ G is not encountered except among very old ($\tau_c > 40$ Myr) or recycled pulsars. Finally, such a CCO, if born in SN 1987A, could explain the non-detection of a pulsar there.

Subject headings: ISM: individual (Kesteven 79, SN 1987A) — pulsars: individual (1E 1207.4−5209, CXOU J185238.6+004020, PSR J1852+0040) — stars: neutron

1. INTRODUCTION

A compact X-ray source, CXOU J185238.6+004020, was found in the center of the supernova remnant (SNR) Kes 79 by Seward et al. (2003). Using *XMM-Newton* in 2004 October, we discovered 105-ms X-ray pulsations from this CCO (Gotthelf et al. 2005, Paper 1), also named PSR J1852+0040. Its pulsed fraction was as high as 86% and it had an apparently thermal X-ray spectrum. From the discovery observations, only an upper limit on its period derivative could be determined, $\dot{P} < 7 \times 10^{-14}$ s s^{-1}, which left the energetics of the NS and the mechanism of its X-ray emission ambiguous. The two most plausible models explored in Paper 1, a rotation-powered pulsar, and accretion from fallback material, each encountered some difficulties.

Here, we present three new observations, two from *XMM-Newton* and one from *Chandra*, that over a 2.4 year span refine the spectral and timing properties of PSR J1852+0040. In addition, we report the negative result of a search for radio pulsations in a deep GBT pointing. From the assembled X-ray timing of PSR J1852+0040, a sensitive new upper limit is obtained on its period derivative, suggesting that the underlying cause of its unusual properties is a weak magnetic field, $B_p < 1.5 \times 10^{11}$ G. Unlike canonical radio pulsars with $B_p \sim 10^{12-13}$ G, a young NS that is weakly magnetized and spinning slowly at birth is able to accrete from material that is thought to remain following a supernova explosion. We discuss this as a model for the properties of radio-quiet CCOs, including the similar pulsar 1E 1207.4−5209.

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2. *XMM-Newton* AND *Chandra* OBSERVATIONS

The two observations previously reported in Paper 1 were obtained with *XMM-Newton* on 2004 October 18 and 23. Two more observations, reported here, were made on 2006 October 8 and 2007 March 20 using the same instrument modes, and exposure times of 30 ks each. The pn CCD of the European Photon Imaging Camera (EPIC; Turner et al. 2003), was operated in "small window" mode with a $4.'3 \times 4.'3$ field-of-view (FOV) and 5.7 ms time resolution to resolve the pulsations of PSR J1852+0040. The EPIC MOS CCDs were exposed in "full frame" mode with a $30'$ diameter FOV and time resolution of 2.7 s. For all three cameras the medium density filter was used. We processed all four observations with Science Analysis System version xmmsas_20060628_1801-7.0.0, using the same techniques as in Paper 1.

A 32 ks *Chandra* observation was performed on 2006 November 23 using the Advanced Camera for Imaging and Spectroscopy (ACIS) operated in continuous-clocking (CC) mode to provide a time resolution of

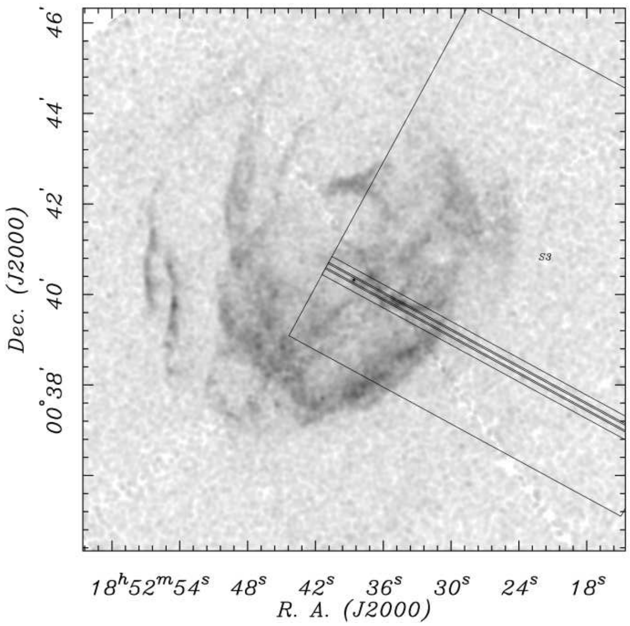

FIG. 1.— Geometry of the 2006 November 23 *Chandra* CC-mode observation of PSR J1852+0040, showing the outline of the S3 CCD and the columns used for source and background extraction, overlaid on the 2001 July 31 ACIS-I observation of Seward et al. (2003). (This broadband image of Kes 79 is square-root scaled to emphasize faint emission features and background.) The counts were summed along the length of the columns, oriented at position angle 241°.5 east of north. Both spectral and timing data for the pulsar were extracted from the six central columns. The background spectrum was obtained from nine neighboring columns on either side (*flanking lines*), separated from the source by a two-column gap.

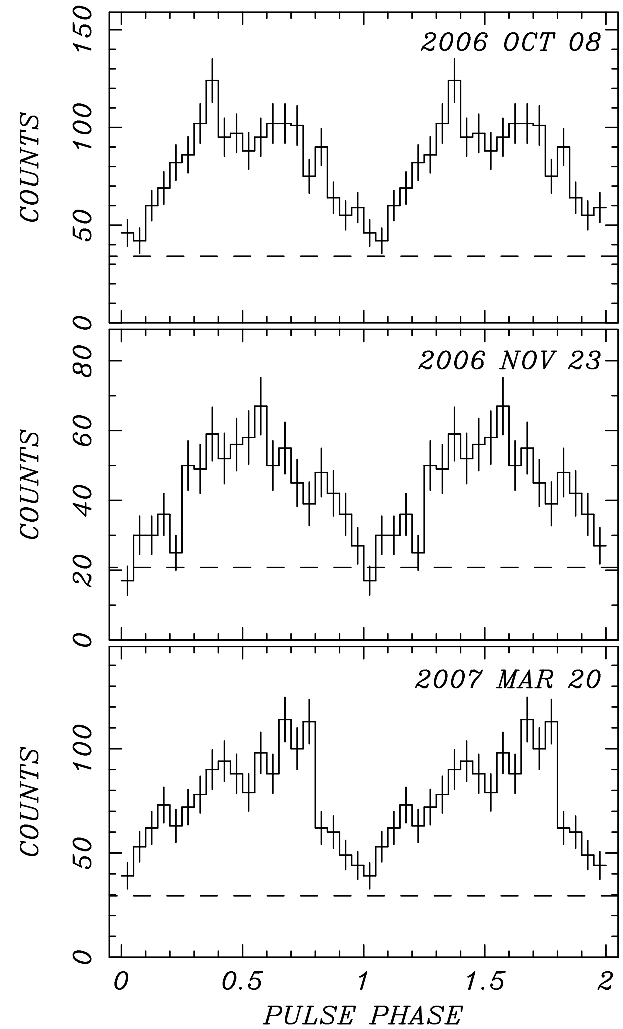

FIG. 2.— Folded light curves of PSR J1852+0040 in the $1-5$ keV band using *XMM-Newton* EPIC pn on 2006 October 8 (*top*), *Chandra* ACIS-S3 in CC mode on 2006 November 23 (*middle*), and *XMM-Newton* EPIC pn on 2007 March 20 (*bottom*). The estimated background level is indicated by the dashed line. Phase zero is arbitrary.

2.85 ms. The back-illuminated ACIS-S3 CCD was used, and the Scientific Instrument Module (SIM) was offset in the $-Z$ direction to place the pulsar $0'.85$ from the edge of the CCD to reduce contamination from the thermal remnant. To achieve the fast timing in CC mode, one spatial dimension of the CCD image is sacrificed by integrating along the column direction during each CCD readout cycle. The geometry of the observation is illustrated in Figure 1, overlaid on an image of Kes 79 previously obtained with ACIS-I in timed exposure mode on 2001 July 31 (Seward et al. 2003). We also reanalyzed the 2001 observation for the spectral properties of the pulsar. During both observations the CCD background count rate was stable and no time filtering was necessary. All photon arrival times were adjusted by the standard processing to account for the spacecraft dithering, and SIM offset in the case of the CC-mode observation. Reduction and analysis of the *Chandra* data are all based on the standard software package CIAO (v3.4) and CALDB (v3.3).

2.1. *Timing Analysis*

Photon arrival times were converted to the solar system barycenter using the *Chandra* derived source coordinates from Paper 1, R.A. = $18^h52^m38^s.57$, decl. = $+00°40'19''.8$ (J2000.0), and signal strength was maximized by selecting the $1-5$ keV energy band. From the *XMM-Newton* observation of 2006 October 8, a Z_1^2 test (Buccheri et al. 1983) localizes the period to $P = 104.912593(20)$ ms with a peak statistic of $Z_1^2 = 88$. The resulting light curve, which has pulsed fraction $f_p = 77\% \pm 15\%$ after accounting for SNR background, is shown in Figure 2. Here, we define the pulsed fraction as $f_p \equiv N(\text{pulsed})/N(\text{total})$, where we choose the minimum of the folded light curve as the unpulsed level. The observation on 2007 March 20 yielded consistent parameters, $P = 104.912609(19)$ ms with $Z_1^2 = 83$ and $f_p = 71\% \pm 15\%$. These new values of f_p are intermediate between the 2004 *XMM-Newton* observations, which yielded $f_p = 86\% \pm 16\%$ and $61\% \pm 16\%$, respectively, weakening the marginal evidence of variability of f_p that was noted in Paper 1. Similar analysis of the *Chandra* observation of 2006 Novemeber 23 yields a formally identical period, $P = 104.912612(19)$ ms with $Z_1^2 = 94$, and f_p consistent with 100%. The pulsed fraction is less reliable in CC-mode data due to systematics of estimating the contamination from SNR background. Table 1 is a summary of all of the available timing data on PSR J1852+0040.

While the new observations extend the sampled time span by a factor of 150 since Paper 1, there is still no

TABLE 1
X-ray Timing of PSR J1852+0040

Mission	Date (UT)	Epoch (MJD)	Duration (s)	Rate[a] (s^{-1})	Period[b] (ms)	f_p[c] (%)
XMM	2004 Oct 18	53,296.001	30,587	0.041(2)	104.912643(18)	86(16)
XMM	2004 Oct 23	53,301.985	30,515	0.046(2)	104.912600(27)	61(16)
XMM	2006 Oct 08	54,016.245	30,243	0.045(2)	104.912593(20)	77(15)
Chandra	2006 Nov 23	54,062.257	32,165	0.022(2)	104.912612(19)	100(16)
XMM	2007 Mar 20	54,179.878	30,506	0.043(2)	104.912609(19)	71(15)

[a]For *XMM-Newton*, background and dead-time corrected count rate in a 15″ radius aperture. Statistical ($\sqrt{N}$) uncertainty in the last digit is given in parentheses.
[b]Period derived from a Z_1^2 test. Period uncertainty is 1σ computed by the Monte Carlo method described in Gotthelf et al. (1999).
[c]Pulsed fraction defined as $f_p \equiv N(\mathrm{pulsed})/N(\mathrm{total})$. Unpulsed level set at lowest point of 20-bin folded lightcurve.

TABLE 2
X-ray Spectral Fits for PSR J1852+0040

Parameter	2001 Jul 31 *Chandra*	2004 Oct 18 *XMM*	2004 Oct 23 *XMM*	2006 Oct 08 *XMM*	2006 Nov23 *Chandra*	2007 Mar 20 *XMM*
Blackbody Model						
$N_{\rm H}$ (10^{22} cm^{-2})	1.1 ± 0.3	1.4 ± 0.3	1.4 ± 0.3	1.4 ± 0.3	1.6 ± 0.3	1.3 ± 0.3
$kT_{\rm BB}$ (keV)	0.50 ± 0.04	0.44 ± 0.04	0.45 ± 0.03	0.46 ± 0.04	0.41 ± 0.04	0.46 ± 0.04
$R_{\rm BB}$ (km)	0.62 ± 0.05	0.92 ± 0.09	0.79 ± 0.09	0.74 ± 0.08	0.96 ± 0.04	0.69 ± 0.09
$A_{\rm BB}$ (10^{10} cm^2)	4.8 ± 0.7	10.7 ± 2.1	7.8 ± 1.7	6.8 ± 1.5	11.5 ± 4.4	6.0 ± 1.5
$F_{\rm BB}$(10^{-13} cgs)[a]	2.0 ± 0.3	1.9 ± 0.3	2.0 ± 0.3	2.0 ± 0.3	1.7 ± 0.4	1.9 ± 0.3
$L_{\rm BB,bol}$(10^{33} cgs)[b]	3.2 ± 0.7	4.3 ± 1.1	3.3 ± 1.0	3.2 ± 1.0	3.5 ± 1.7	2.9 ± 1.1
$\chi^2_\nu(\nu)$	0.71(18)	0.85(68)	0.67(70)	0.86(69)	0.88(22)	0.67(69)
Power-law Model						
$N_{\rm H}$ (10^{22} cm^{-2})	$2.6^{+0.7}_{-0.4}$	$3.2^{+0.6}_{-0.6}$	$3.1^{+0.6}_{-0.5}$	$3.2^{+0.6}_{-0.5}$	$3.4^{+0.8}_{-0.6}$	$3.2^{+0.7}_{-0.6}$
Γ	$4.1^{+0.7}_{-0.4}$	$4.9^{+0.7}_{-0.6}$	$4.9^{+0.6}_{-0.5}$	$4.8^{+0.6}_{-0.5}$	$5.3^{+0.8}_{-0.7}$	$4.9^{+0.6}_{-0.6}$
$F_{\rm PL}$(10^{-13} cgs)[a]	2.0 ± 0.6	1.9 ± 0.43	2.0 ± 0.4	2.1 ± 0.5	1.8 ± 0.4	1.9 ± 0.4
$L_{\rm PL}$(10^{33} cgs)[c]	1.2 ± 0.4	1.1 ± 0.2	1.2 ± 0.2	1.2 ± 0.3	1.1 ± 0.3	1.2 ± 0.3
$\chi^2_\nu(\nu)$	0.94(18)	0.82(68)	0.68(70)	0.78(69)	0.81(22)	0.71(69)

Note. — Uncertainties are 68% confidence intervals for two interesting parameters. Luminosities are computed for $d = 7.1$ kpc.
[a]Absorbed flux in the $1-5$ keV band in units of ergs cm^{-2} s^{-1}.
[b]Unabsorbed, bolometric blackbody luminosity in units of ergs s^{-1}.
[c]Absorbed luminosity in the $1-5$ keV band in units of ergs s^{-1}. This corrects an error in Table 2 of Paper 1.

significant detection of a period derivative. A χ^2 fit to the five measurements of P yields the formally negative $<\dot P> = (-3.4\pm2.7)\times10^{-16}$ s s^{-1} that is, however, consistent with zero at the $\approx 1\sigma$ level. We are unable to link any of the observations with a definite cycle count in order to improve on this measurement. If we adopt the 2σ upper limit $\dot P < 2.0\times10^{-16}$, the dipole spin-down formalism for an isolated pulsar implies an energy loss rate $\dot E = -I\Omega\dot\Omega = 4\pi^2 I\dot P/P^3 < 7\times10^{33}$ ergs s^{-1}, surface magnetic field strength $B_p = 3.2\times10^{19}\sqrt{P\dot P} < 1.5\times10^{11}$ G, and characteristic age $\tau_c \equiv P/2\dot P > 8$ Myr. These derived quantities pose problems for a rotation-powered X-ray source, as discussed in §4.1.

2.2. *Spectral Analysis*

Following the analysis method in Paper 1 for each *XMM-Newton* observation, spectra from the two EPIC MOS cameras (MOS1, MOS2) were co-added. The EPIC MOS and EPIC pn spectra were then fitted simultaneously using the `XSPEC` (v12.21) package. The results of spectal fits using either a blackbody or an absorbed power-law model are presented in Table 2. An acceptable χ^2 statistic is obtained using either model. However, the blackbody is preferred over the power law based on its derived column density of $N_{\rm H} = (1.4\pm0.3)\times10^{22}$ cm^{-2}, which is consistent with that found for the SNR ($N_{\rm H} \approx 1.6\times10^{22}$ cm^{-2}, Sun et al. 2004). The fitted column density for the power-law model, $N_{\rm H} = 3.2^{+0.6}_{-0.5}\times10^{22}$ cm^{-2}, is significantly larger than the integrated 21 cm Galactic value of 2×10^{22} cm^{-2} in this direction (Dickey & Lockman 1990). The best-fit blackbody model yields temperature $kT_{\rm BB} = 0.46\pm0.04$ keV (see Fig. 3). Adopting a distance $d = 7.1$ kpc from Case & Bhattacharya (1998), the bolometric blackbody luminosity $L_{\rm BB,bol} \approx 3.0\times10^{33}$ ergs s^{-1}, corresponding to blackbody area $A_{\rm BB} \approx 7\times10^{10}\,(d/7.1\ {\rm kpc})^2$ cm^2 or $\approx 0.4\%$ of the NS surface. These results are consistent with the spectral parameters from the previous *XMM-Newton* observations in 2004 October, described in Paper 1 and summarized

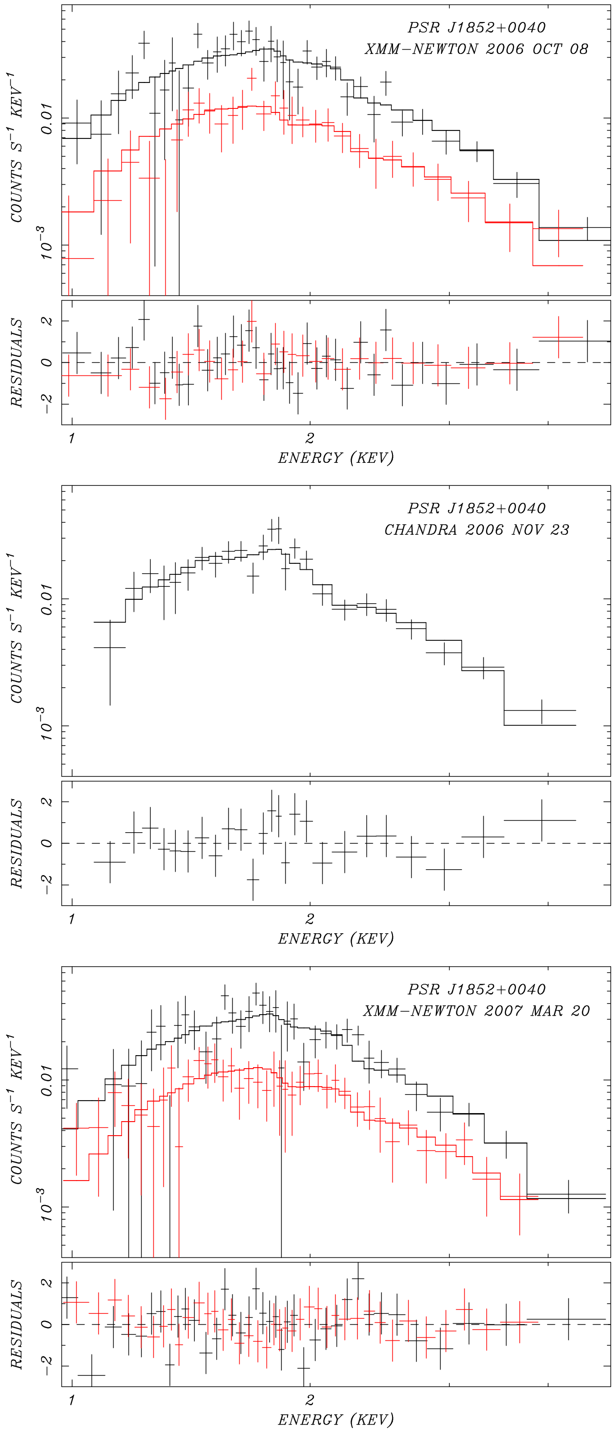

Fig. 3.— X-ray spectra of PSR J1852+0040 in Kes 79. *Top*: The *XMM-Newton* spectrum on 2006 October 8. Data from the EPIC pn (*black, upper*) and EPIC MOS (*red, lower*) with the best-fit blackbody model using parameters in Table 2. The residuals from the fits are in units of σ. *Middle*: Spectrum on 2006 November 23 from the *Chandra* ACIS-S3 in CC mode. *Bottom*: The *XMM-Newton* spectrum on 2007 March 20. [*See the electronic version of the Journal for a color version of this figure.*]

here in Table 2, indicating that the flux and spectrum have remained steady.

The *Chandra* spectra from the 2001 and 2006 observations were each prepared by grouping a minimum of 40 counts per channel, and fitted using the `XSPEC` software. The standard spectral response matrices were generated for the target location on the CCD and all spectra were corrected for the effects of charge-transfer inefficiency; however, the spectral gain is not calibrated well in CC-mode. The resulting spectral parameters from the *Chandra* observations, listed in Table 2, are similar to the ones from *XMM-Newton*. The blackbody fits to the new *XMM-Newton* and *Chandra* spectra are shown in Figure 3.

3. SEARCH FOR A RADIO PULSAR

On 2002 October 29 we observed the location of CXOU J185238.6+004020 with the ATNF Parkes telescope in NSW, Australia. At that time the period of the pulsar was not yet known, so we employed standard pulsar searching techniques. We used the central beam of the multibeam receiver at a frequency of 1374 MHz, with 96 channels across a bandwidth of 288 MHz in each of two polarizations. The integration time was 6.8 hr, during which total-power samples were obtained every 0.73 ms and recorded for off-line analysis. We searched the dispersion measure range 0–2500 $\mathrm{cm^{-3}}$ pc (twice the maximum Galactic DM predicted for this line of sight by the Cordes & Lazio 2000 electron density model; for the distance of 7.1 kpc, the predicted DM is 440 $\mathrm{cm^{-3}}$ pc). The search followed closely that described in more detail in Camilo et al. (2006). No promising candidate periods were identified.

Following the X-ray discovery of the pulsar period, we made a deeper search using the GBT. We did this on 2005 June 10, observing the pulsar for 11.1 hr with the Spigot spectrometer (Kaplan et al. 2005), sampling 768 frequency channels across a bandwidth of 600 MHz centered on 1950 MHz every 81.92 μs. In addition to performing a standard blind search, we also folded the data at a number of DMs for periods close to the X-ray value to increase the sensitivity, but again found no candidates. We used the PRESTO software package to analyze these data (Ransom 2001; Ransom et al. 2002).

Applying the standard modification to the radiometer equation, assuming a quasi-sinusoidal pulse shape (as in X-rays; see Fig. 2), and accounting for a sky temperature at this location of 5 K, we were sensitive to a pulsar with period 105 ms having a period-averaged flux density at 2 GHz $\gtrsim$ 12 μJy. Converting this to the more common 1.4 GHz pulsar search frequency, using a typical spectral index of −1.6 (Lorimer et al. 1995), results in $S_{1.4} \lesssim 0.02$ mJy. For a distance of ≈ 7 kpc, this corresponds to a pseudo-luminosity limit of $L_{1.4} \equiv S_{1.4} d^2 \lesssim 1\,\mathrm{mJy\,kpc^2}$. Only one young radio pulsar has a smaller radio luminosity than this (the pulsar in 3C58; Camilo et al. 2002).

Based on these results, it is therefore somewhat unlikely that PSR J1852+0040 is presently a radio pulsar beaming toward the Earth. More likely, it is either beaming away (observed radio pulsars with similar periods, or ages $\lesssim 10$ kyr, have beaming fractions of ~ 0.3; see Tauris & Manchester 1998), or not an active radio pulsar at all.

4. DISCUSSION

4.1. *Rotation-Powered Pulsar?*

Potential obstacles to the interpretation of PSR J1852+0040 as a rotation-powered pulsar were identified in Paper 1. The newly reduced upper limit on its $\dot{P}$, by more than 2 orders of magnitude, turns those difficulties into major objections. First, the X-ray luminosity of PSR J1852+0040, $L_{\rm bol} \approx 3 \times 10^{33}\,(d/7.1\ {\rm kpc})^2$ ergs s^{-1}, is comparable to the 2σ upper limit on its spin-down power, $\dot{E} < 7 \times 10^{33}$ ergs s^{-1}. Thus, it may be difficult to power the X-ray source with spin-down energy. Since the X-ray spectrum is consistent with thermal emission, what about residual cooling of the neutron star? While the X-ray luminosity of PSR J1852+0040 is consistent with minimal NS cooling curves for an age of 10^{3-4} yr (Page et al. 2004), its blackbody temperature implies an emitting area that is just $\approx 0.4\%$ of the NS surface. Even taking into account that, in a real NS atmosphere, a blackbody fit overestimates the effective temperature and underestimates the area, the highly modulated X-ray pulse must come from a small hot spot. Although anisotropic conduction in a magnetized NS can enforce temperature gradients on the surface, such models (Geppert et al. 2004; Pérez-Azorín et al. 2006) do not show spots as small and as hot as observed here. Instead, an external source of localized heating may be needed.

The open-field-line polar cap is the most likely target area for external heating of the NS surface, with the energy ultimately drawn from rotation. The canonical area of the polar cap is $A_{\rm pc} = 2\pi^2 R^3/Pc \approx 1 \times 10^{10}$ cm^2; this is $\sim 14\%$ of the area implied by the blackbody fit to the X-ray spectrum. Among theories of polar-cap heating, a maximum thermal luminosity is predicted by Wang et al. (1998) from the outer-gap model for γ-ray pulsars. In this analysis, the X-ray luminosity of the hot polar cap is limited by the Goldreich-Julian $e^{\pm}$ current flow of $\dot{N}_0 \approx 2 \times 10^{31}\,(P/0.105\,{\rm s})^{-2}\,(B_p/10^{11}\,{\rm G})$ s^{-1} depositing an average energy per particle $E_f \approx 4.3$ ergs. The maximum luminosity is $L_{\rm bol} \approx f E_f \dot{N}_0 < 4 \times 10^{31}$ ergs s^{-1}. Here, the fraction f of the current reaching the surface is set to its estimated maximum value of $\frac{1}{2}$. Polar-cap heating models of Harding & Muslimov (2001, 2002) predict even less X-ray luminosity than Wang et al. (1998). Therefore, current theories fall short of predicting the temperature and luminosity of the X-ray emission from PSR J1852+0040 in the context of a spinning-down neutron star.

After the unexplained X-ray properties, a lesser problem for PSR J1852+0040 as an isolated pulsar is its characteristic age $\tau_c \equiv P/2\dot{P} > 8$ Myr, which exceeds by 3 orders of magnitude the SNR age, estimated dynamically as $5.4-7.5$ kyr (Sun et al. 2004). This would require the pulsar to have been born at its current period to be associated with the SNR. While not fundamentally contradicting the rotation-powered hypothesis, this result is a definite example in support of a recent population analysis that favors a wide distribution of radio pulsar birth periods (Faucher-Giguère & Kaspi 2006), even though PSR J1852+0040 is not itself a radio pulsar. Furthermore, as magnetic field is generated by a turbulent dynamo whose strength depends on the rotation rate of the proto-neutron star (Thompson & Duncan 1993), it is natural that long-period pulsars would have the weaker B-fields at birth, and the model of Bonanno et al. (2006) shows this. Bonanno et al. (2006) also find that a slowly rotating NS should have its B-field confined to small-scale regions, with the global dipole that is responsible for spin-down absent.

Finally, we note that there are no young radio pulsars known with $B_p < 10^{11}$ G. All such weakly magnetized radio pulsars are either very old, with $\tau_c > 40$ Myr (Manchester et al. 2005)[3], or are recycled, the result of accretion from a binary companion. Faucher-Giguère & Kaspi (2006) conclude that there is no evidence for magnetic field decay during the radio emitting life of a pulsar, so the observered distribution of B_p should resemble its birth distribution. Among the B_p distribution of ordinary (not recycled) radio pulsars, PSR J1852+0040 is certainly in the bottom 10%, and maybe lower. PSR J1852+0040 may become a radio pulsar in the far future, but its weak B-field may be preventing radio emission now by permitting accretion. While there is no evidence of a close binary companion in the timing of PSR J1852+0040 (see Paper 1), it is possible that low-level accretion of SN debris prevents it and other radio-quiet CCOs from becoming radio pulsars for thousands or even millions of years. We next consider whether the hypothesis of accretion from such a fallback disk (e.g., Alpar 2001; Shi & Xu 2003; Ekşi et al. 2005) better explains the X-ray timing and spectral properties of PSR J1852+0040.

4.2. *Fallback Accretion?*

The fact that $\dot{P}$ is so small leads us to review the viability of accretion of supernova debris through a disk. The X-ray luminosity of PSR J1852+0040 can be powered by accretion of $\dot{m} \approx 3 \times 10^{13}$ g s^{-1}, or only ≈ 0.1 lunar masses of supernova debris over the past 7.5 kyr. The main barrier to disk accretion is the speed-of-light cylinder, of radius $r_\ell = cP/2\pi = 5 \times 10^8$ cm. If an accretion disk cannot penetrate the light cylinder, the NS cannot interact with the disk, and it behaves as a isolated pulsar. But if B_p is as small as 10^{10} G, accretion at a rate $\dot{M} \geq 10^{13}$ g s^{-1} can penetrate the light cylinder, since the magnetospheric radius is then

$$r_m = 3.2 \times 10^8\, \mu_{28}^{4/7}\, \dot{M}_{13}^{-2/7} \left(\frac{M}{M_\odot}\right)^{-1/7}\ {\rm cm}, \qquad (1)$$

where the magnetic moment $\mu = B_p R^3/2 \approx 10^{28} B_{p,10}$ G cm^3. If so, the system is in the propeller regime, in which matter flung out from r_m at a rate $\dot{M}$ takes angular momentum from the NS, causing it to spin down. The propeller spin-down rate is estimated as

$$\dot{P} \approx 2\, \dot{M}\, r_m^2\, I^{-1}\, P \left(1 - \frac{P}{P_{\rm eq}}\right) \qquad (2)$$

(e.g., Menou et al. 1999; Ekşi et al. 2005). Here $I \approx 10^{45}$ g cm^2 is the NS moment of inertia, and $P_{\rm eq} = 3.2\, \mu_{28}^{6/7}\, \dot{M}_{13}^{-3/7}\, (M/M_\odot)^{-5/7}$ s is the equilibrium, or minimum period for disk accretion that is reached when $r_m \leq r_{\rm co}$. The corotation radius is $r_{\rm co} = [GM(P/2\pi)^2]^{1/3} = 3.7 \times 10^7$ cm.

[3] ATNF Pulsar Catalogue, version 1.29, http://www.atnf.csiro.au/research/pulsar/psrcat/

While we have not measured a significant $\dot{P}$ in order to determine the needed $\dot{M}$, we can adopt the 2σ upper limit, $\dot{P} < 2.0 \times 10^{-16}$, as an estimate of $\dot{P}$. Combining equations (1) and (2), we have in the propeller scenario

$$\dot{P} \approx 2.2 \times 10^{-16}\, \mu_{28}^{8/7}\, \dot{M}_{13}^{3/7} \left(\frac{M}{M_\odot}\right)^{-2/7} I_{45}^{-1} \left(\frac{P}{0.105\ \mathrm{s}}\right) \left(1 - \frac{P}{P_{\mathrm{eq}}}\right). \quad (3)$$

We must distinguish here between $\dot{M}$, the matter expelled that is responsible for the torque on the NS, and $\dot{m} \approx 3 \times 10^{13}$ g s^{-1}, the matter accreted, which is responsible for the X-ray emission from the surface, presumably at a magnetic pole of the neutron star. For the propeller model to be self-consistent, $\dot{M}$ must be $> \dot{m}$, which is possible according to equation (3) as long as $B_p < 10^{10}$ G. Even so, $\dot{M}$ does not contribute significantly to the X-ray luminosity because of the much weaker gravitational potential at the magnetospheric radius r_m from which it is expelled. If B_p is as small as 7×10^8 G, then PSR J1852+0040 is not a propeller, but a "slow rotator," with $r_m \leq r_{\mathrm{co}}$ and $P_{\mathrm{eq}} \leq P$. In this spin-up regime, it would be even more difficult to measure $\dot{P}$, since

$$\dot{P} \approx -1.3 \times 10^{-18}\, \mu_{27}^{2/7}\, \dot{m}_{13}^{6/7} \left(\frac{M}{M_\odot}\right)^{3/7} \left(\frac{P}{0.105\ \mathrm{s}}\right)^{2} \quad (4)$$

(Ghosh & Lamb 1979).

These equations also apply during the prior evolution of the pulsar and show that, even if the accretion rate was orders of magnitude higher in the past, the spin-up and spin-down times $P/\dot{P}$ are much longer than the age of the SNR. There has not been enough time for propeller accretion to have spun the pulsar down from a much smaller P, so even in this model it was born at essentially its present P.

Thus, we regard either propeller spindown or accretion in a weak magnetic field as consistent with the X-ray spectral and timing properties of PSR J1852+0040. If accreting, its emitting region could be larger than the open-field-line polar cap because it would be connected to magnetic field lines extending to r_m, which is $< r_\ell$. Neither equation (3) nor equation (4) requires there to be much torque noise at the level that present data can measure. While detected flickering is an indicator of accretion in X-ray binaries even in quiescence (Rutledge et al. 2007), we do not have strong evidence of variability of PSR J1852+0040. But it is not clear that the processes in binaries can be extrapolated to accretion at such low rates from a fossil disk. Finally, because of the large distance and interstellar extinction to PSR J1852+0040, as well as its crowded optical field, existing optical data do not rule out the presence of a fallback accretion disk around PSR J1852+0040 (see Paper 1 for details).

4.3. *Comparison with 1E 1207.4−5209 and Other CCOs*

Difficulties in understanding the timing behavior of another CCO, the 424-ms pulsar 1E 1207.4−5209 (Zavlin et al. 2004; Woods et al. 2006), were resolved recently by Gotthelf & Halpern (2007), who showed that it is a steady rotator with $\dot{E} < 1.5 \times 10^{32}$ ergs s^{-1} and $B_p < 3.5 \times 10^{11}$ G. This makes 1E 1207.4−5209 very similar to PSR J1852+0040 in its physical parameters. Accretion from a fossil disk of supernova debris (Alpar 2001; Shi & Xu 2003; Ekşi et al. 2005; Liu et al. 2006) was one of the theories considered by Zavlin et al. (2004) to explain the now defunct timing irregularities of 1E 1207.4−5209. But accretion may still be needed to explain the radio-quiet nature of 1E 1207.4−5209, and the details of its X-ray spectrum. However, unlike PSR J1852+0040, upper limits on optical/IR emission from 1E 1207.4−5209 are comparable to what is expected from a geometrically thin, optically thick disk accreting at the rate required to account for its X-ray luminosity (Zavlin et al. 2004; Wang et al. 2007). Therefore, it may prove necessary to invoke a radiatively inefficient flow, or perhaps even accretion of solid particles (Cordes & Shannon 2006), in order to proceed with this theory for 1E 1207.4−5209. We propose that this may be the first phase in the life of those neutron stars born rotating slowly, and with weak magnetic fields.

A unique phenomenon displayed by 1E 1207.4−5209 is the set of broad absorption lines in its soft X-ray spectrum. They are centered at 0.7 keV and 1.4 keV (Sanwal et al. 2002; Mereghetti et al. 2002), and possibly at 2.1 keV and 2.8 keV (Bignami et al. 2003; De Luca et al. 2004), although the reality of the two higher-energy features has been disputed (Mori et al. 2005). Proposed absorption mechanisms include electron cyclotron in a weak (8×10^{10} G) magnetic field (Bignami et al. 2003; De Luca et al. 2004), atomic features from singly ionized helium in a strong (2×10^{14} G) field (Sanwal et al. 2002; Pavlov & Bezchastnov 2005), and oxygen or neon in a normal (10^{12} G) field (Hailey & Mori 2002; Mori & Hailey 2006). A detailed critique of these models is beyond the scope of this paper. We only remark that: (1) local values of B measured from X-ray spectral features may differ from the global dipole B that is measured by timing, especially if the dipole component is weak (Bonanno et al. 2006), and (2) the attractive feature of the electron cyclotron model for 1E 1207.4−5209, the equal energy spacing of its lines, is in harmony with the present work on PSR J1852+0040 which, by different arguments, requires a weak surface magnetic field.

Xu et al. (2003) argued that electron cyclotron harmonics of roughly equal depth could be produced because, even though the oscillator strength of the harmonic is much less than that of the fundamental, resonant cyclotron radiative transfer could equalize the line strengths. Liu et al. (2006) also explained how objections to the cyclotron model involving the relative oscillator strengths can be overcome by assuming that the fundamental is optically thick while the harmonic is optically thin, resulting in comparable equivalent widths. They also proposed a specific geometry that accounts for the strength of the lines, which also accommodates the small pulsed fraction observed from 1E 1207.4−5209. This involves a column rising along the magnetic axis and viewed from the side. Finally, Liu et al. (2006) remarked that such a column may be more easily maintained in an accretion scenario.

While the lower-quality spectra of PSR J1852+0040 do not yet show evidence of absorption features, cyclotron lines could be weak if either the column density in which

they are formed or the viewing geometry is not favorable, or especially if the magnetic field is so small as to shift them below the observable X-ray band. The fitted interstellar column density to PSR J1852+0040, $N_{\rm H} = 1.4 \times 10^{22}$ cm^{-2}, is much larger than that to 1E 1207.4−5209, $N_{\rm H} = (3-10)\times10^{20}$ cm^{-2} (Mereghetti et al. 2002). Therefore, the soft X-ray region in which the strongest lines in 1E 1207.4−5209 are seen is partly suppressed in the case of PSR J1852+0040. Finally, it is possible that the X-ray spectrum of PSR J1852+0040 is not a pure blackbody as fitted, but is affected by unmodelled, broad cyclotron absorption at the low-energy end.

The half dozen CCOs (for a review, see Pavlov et al. 2004) are similar in their X-ray luminosities and temperatures. Therefore, they may be compatible with the model that we propose for PSR J1852+0040 and 1E 1207.4−5209. The only piece of evidence that sharply contradicts such unification is the apparent historical outburst of the CCO in the Cas A SNR that was inferred from infrared light echos detected with the *Spitzer Space Telescope* (Krause et al. 2005). The geometry and sharpness of the echos implies that beamed emission from the central source flared for less than a few weeks about 50 years ago, and the radiation reprocessed into thermal emission from dust require an equivalent isotropic flare of $\sim 2 \times 10^{46}$ ergs. Because such energetic outbursts are seen on similar timescales from soft gamma-ray repeaters, Krause et al. (2005) proposed that the Cas A CCO is a quiescent magnetar, at the other extreme of magnetic field strength from PSR J1852+0040. A convincing determination of the magnetic field strengths of the Cas A CCO and others will have to await discovery of their pulsations.

4.4. *Application to SN 1987A*

It has long been recognized that the non-detection of the expected pulsar in the remnant of SN 1987A can be explained if the NS was born with a weak magnetic field or a long rotation period (Ögelman & Alpar 2004), and that several CCOs, including the one in Cas A, would be undetected if placed in SN 1987A (Graves et al. 2005). However, it was not established until now that a CCO can have essentially the same spin-down luminosity at birth that it has at an age of 400 or 10^4 yr, i.e., that it is born with both a weak B-field and a long P. This new result means that a common type of neutron star can emit less than the observed limits from SN 1987A even if 100% of its spin-down power is reprocessed into IR emission by dust in the surrounding SN ejecta. The relevant luminosity limits to be satisfied for a point source inside the ring of SN 1987A are $L_x(2-10\,{\rm keV}) < 1.5\times10^{34}$ ergs s^{-1} corrected for extinction (Park et al. 2004), $L(2900-9650\,\text{Å})$ $< 8\times10^{33}$ ergs s^{-1} corrected for dust absorption (Graves et al. 2005), and $L(10\,\mu{\rm m}) < 1.5\times10^{36}$ ergs s^{-1} for dust emitting at $T \approx 90-100$ K (Bouchet et al. 2004). This mid-IR luminosity can be accounted for by radioactive decay of ^{44}Ti, and therefore represents a very conservative upper limit on the spin-down power of an embedded pulsar. At an age of $10-20$ yr, a cooling NS need emit only $\approx 3\times10^{34}$ ergs s^{-1} of soft X-rays at a temperature of 2.5×10^6 K (Yakovlev et al. 2002), some of which is absorbed by SN ejecta or ISM in the LMC. The upper limit on spin-down power from PSR J1852+0040, $\dot E < 7\times10^{33}$ ergs s^{-1}, is a challenge to detect in SN 1987A, and $\dot E < 1.5\times10^{32}$ ergs s^{-1} from 1E 1207.4−5209 would be impossible. So we conclude that a CCO is a promising model for the unseen NS in SN 1987A.

5. CONCLUSIONS AND FUTURE WORK

We obtained three new X-ray timing points on PSR J1852+0040 that, in combination with two previous observations, reveal no significant change in spin period on time scales ranging from 1 week to 2.4 yr. In the dipole spin-down formalism, this implies $\dot E < 7\times10^{33}$ ergs s^{-1} and $B_p < 1.5\times10^{11}$ G. Such a low B-field is not seen in young radio pulsars, and while it does not demand a special explanation, it does favor accretion as a source of the small, hot thermal region that is responsible for the highly modulated X-ray pulsations, which may exceed the spin-down power of the isolated NS, and strains any plausible interior cooling or external heating model.

We showed that the observered spin period, 105 ms, in combination with a weak field, $B_p \sim 10^{10}$ G, would allow disk accretion in the propeller regime, which may be a more satisfactory model overall. If B_p is even weaker, $< 10^9$ G, PSR J1852+0040 could be a "slow" accretor. Considering also the properties of the CCO 1E 1207.4−5209, we speculated that this class may have weak magnetic fields as a result of slow natal rotation, which enables them to accrete. While we do not decisively favor accretion over a rotation-powered pulsar, we emphasize that for PSR J1852+0040 a weak magnetic field is an unavoidable feature of either interpretation. Such low-B births may be very common if they also occurred in Cas A and/or SN 1987A.

A radio pulsar detection of PSR J1852+0040 would demonstrate cleanly that it is rotation powered, but our negative results so far are inconclusive because there are several reasons why a rotation-powered pulsar may not be detected in radio. Continued X-ray monitoring will provide a more sensitive test for spin-down or accretion torques, perhaps eventually in a definitive manner, and more evidence of whether or not the X-ray flux and pulse profile are variable. It is now important to obtain a phase-connected timing solution, the most efficient and sensitive method of measuring a small $\dot P$. If obtained soon, a well-timed series of observations should allow a coherent solution to be fitted retroactively back to 2004. Also, considering the possibility that a weak magnetic field and accretion may be responsible for the absorption lines in the soft X-ray spectrum of 1E 1207.4−5209, a deeper X-ray spectral study of PSR J1852+0040 may be revealing. Finally, in order to test the general applicability of these ideas to the class of CCOs, more sensitives searches for their pulsations are required.

This investigation is based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. Support for this work was provided by NASA through *XMM* grant NNX06AH95G and *Chandra* Award SAO GO6-7048X issued by the *Chandra* X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of

NASA under contract NAS8-03060. The GBT is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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